Smart optical writing head design for laser-based manufacturing

Amin, M. Junaid, Riza, Nabeel

M. Junaid Amin, Nabeel A. Riza, "Smart optical writing head design for laser-based manufacturing," Proc. SPIE 8967, Laser Applications in Microelectronic and Optoelectronic Manufacturing (LAMOM) XIX, 89671D (6 March 2014); doi: 10.1117/12.2038352

SPIE.

Event: SPIE LASE, 2014, San Francisco, California, United States

Smart Optical Writing Head Design for Laser-Based Manufacturing

M. Junaid Amin and Nabeel A. Riza[a,b*]

[a,b]Electrical and Electronic Engineering, School of Engineering, University College Cork (UCC), College Road, Cork, Ireland
*email: n.riza@ucc.ie

ABSTRACT

Proposed is a smart optical writing head design suitable for high precision industrial laser based machining and manufacturing applications. The design uses an Electronically Controlled Variable Focus Lens (ECVFL) which enables the highest achievable spatial resolution of writing head spot sizes for axial target distances reaching 8 meters. A proof-of-concept experiment is conducted using a visible wavelength laser with a collimated beam that is coupled to beam conditioning optics which includes an electromagnetically actuated deformable membrane liquid ECVFL cascaded with a bias convex lens of fixed focal length. Electronic tuning and control of the ECVFL keeps the laser writing head far-field spot beam radii under 1 mm that is demonstrated over a target range of 20 cm to 800 cm. Applications for the proposed writing head design, which can accommodate both continuous wave and pulsed wave sources, include laser machining, high precision industrial molding of components, as well as materials processing requiring material sensitive optical power density control.

Keywords: Industrial machining, programmable optics, laser-based cutting

1. INTRODUCTION

Lasers are playing an increasingly important role in non-contact machining processes in industries relating to aircraft, automobile, home appliances, and electronic and photonic component sectors. Machining of metallic, non-metallic, optical, and ceramic materials to a desired work piece profile involves the functions of not only cutting, but also drilling, melting, grooving as well as precision milling. Extensive literature is present on laser-based cutting techniques involving both continuous and pulsed sources and the use of different machining process optimization techniques [1-9]. Successful laser-based machining involves adapting the incident laser spot, i.e., laser beam characteristics, to the substrate material's thermal and optical properties preventing undue loss or damage to the material, ensuring a high Material Removal Rate (MRR) as well as achieving the desired profile. Hence, laser beam characteristics including the beam size and optical power density play pivotal roles in determining the quality of laser machining.

Fig. 1 shows a Gaussian laser beam propagating through space with a $1/e^2$ minimum beam waist radius w_0 located a distance d_0 inside the laser module. This unconditioned raw laser beam increases in transverse beam size as it traverses along the axial (i.e., laser beam) direction. The X-Y scan mirror is included for directionality. For applications requiring similarly high precision cutting ability at both substrate planes 1 and 2, the Fig. 1 design fails to provide necessary flexibility and would need to be mounted on a movable mechanical platform to adjust for the increasing beam size. Similarly, laser systems incorporating fixed focus lenses (not shown here) designed for specific applications are not suited for machining tasks requiring cutting capabilities over a large distance range, e.g., > 50 cm in the axial direction. Therefore it is desired to have an optical head which is not restricted to having its smallest size in a single axial plane, and is completely programmable to control laser beam propagation properties.

Such a smart optical writing head design is proposed in this paper which addresses the issues faced by unconditioned as well as fixed focus laser beams. The proposed design, based on a recent laser scanning sampling head design for image

Laser Applications in Microelectronic and Optoelectronic Manufacturing (LAMOM) XIX, edited by Yoshiki Nakata, Xianfan Xu, Stephan Roth, Beat Neuenschwander, Proc. of SPIE Vol. 8967, 89671D

· doi: 10.1117/12.2038352

acquisition [10], uses an ECVFL along with a bias lens of fixed focal length to achieve desired spot diameters over an experimentally demonstrated distance range up-to 8 meters. This allows the machining process to not only better adapt properties of the substrate and incorporate material specific optical and thermal properties, but also account for a large size substrate requiring precision drilling or hole-punching, such as those in automobile or aircraft industries.

2. SMART OPTICAL WRITING HEAD DESIGN

The proposed smart optical writing head design is shown in Fig. 2. Laser light of wavelength λ exits the laser module to strike a Microscope Objective (MO) and is focused onto a Pinhole (P) acting as a spatial filter. A collimation lens S captures the emanating airy pattern and the collimated beam traverses through to the ECVFL having an illuminated diameter D_e, placed a distance d_1 from the laser module. The laser continues along its path to strike a Bias Lens (BL), having an illuminated diameter D_b, which is placed at a distance d_S from the ECVFL. Since an approximate plane wave is entering the two lens system (ECVFL-BL), the resulting net focal length F_{net} is found using the geometric optics expression [11]:

$$\frac{1}{F_{net}} = \frac{1}{F_e} + \frac{1}{F_b} - \frac{d_S}{F_e F_b} \quad , \tag{1}$$

where F_e and F_b are focal lengths of ECVFL and BL, respectively. Assuming the values of F_e and F_b are such that the beam is focused to the right of BL, L is defined as the distance from BL to that focus point along the propagation axis, and has the expression:

$$L = \frac{F_b \left(F_e - d_S\right)}{F_e + F_b - d_S} \quad . \tag{2}$$

The derivation of the expression for L can be seen in [10] or in suitable geometric optics textbooks. The key point here is that for a Fig. 2 design having a fixed F_b, and d_S, L is a function of F_e which is electronically tunable by the user. Therefore the point of focus of the optical head is controlled via a no-moving parts mechanism dictated by the parameter F_e, for a given F_b and d_S.

Fig. 3 shows a geometric optics diagram displaying the effect of F_e variation on L and the laser beam size. Beams B_1 and B_2 labelled in Fig. 3 are produced via different ECVFL settings, i.e., by having $F_e = F_{e1}$ and $F_e = F_{e2}$, respectively. B_1 focuses at Plane P_1, i.e., has a minimum beam diameter at P_1, while B_2 at the same plane has a relatively large beam diameter. At Plane P_2, B_2 has its minimum diameter while B_1, shown by the dashed propagation lines has a greater beam diameter, demonstrating spot size variation capability of the proposed design. For beam B_1, $L = L_1$, and for B_2, $L = L_2$ where $L_2 > L_1$. The laser spot diameter $2w_{min}$ of the focused airy spot at the focus point of the laser beam in the Fig. 2 design is given by the expression [11]:

$$2w_{min} = 2.44 \times \lambda \times \left(\frac{F_{net}}{D_{net}}\right) \quad , \tag{3}$$

where D_{net}, the equivalent diameter of the two-lens system, is equal to D_e via geometrical optics. Note that the ratio F_{net}/D_{net} is also known as the f-number of the 2 lens system and is a function of the variable F_e. Eqn. (3) relates to the spot size at the minimum spot of the beam. The spot size of an arbitrary beam illuminating a substrate material placed a distance d_M from BL is found via geometrical optics by:

$$w_M = D_b \times \frac{\left\| L - d_M \right\|}{L} \quad . \tag{4}$$

Note that as d_M gets closer to L, the distance at which the beam is focussed, w_M approaches w_{min}. A more accurate expression for w_M may be found via computation of Fresnel diffraction integrals applicable to the system, though for simplicity, that is not mentioned here.

In comparison to the optics of the proposed programmable optical writing head design, the beam radius w_c of an unconditioned Gaussian laser beam at a material distance d_M has the expression [12]:

$$w_c = w_0 \sqrt{1 + \left(\frac{\lambda (d_0 + d_1 + d_S + d_M)}{\pi w_0^2} \right)^2}. \tag{5}$$

R, the writing head reduction factor, is used to quantify improvement in relative optical head size due the proposed optical writing head design, and is defined as:

$$R = \frac{w_c}{w_{min}} \quad . \tag{6}$$

Since a laser beam cuts in 2-axis making up the transverse direction, R^2 will be used instead of R as measurement of design effectiveness. Eqn. (5) will be used as comparison to the proposed design demonstration results, which is presented in the next section.

3. EXPERIMENT

For a proof of concept demonstration of the proposed smart optical writing head design, a 632.8 nm wavelength continuous wave Melles Griot He-Ne laser having 10mW power and w_0 = 325 µm is deployed as the laser source. MO has magnification 10x, P has 10 µm diameter, S has a focal length of 5 cm and F_b = 20 cm. Optotune's EL-6-18 ECVFL model is used in the experiment which has D_e = 6 mm. A CCD imager, Sony's XC-77, was used to capture and measure minimum beam spot radii w_{min} at different distances. Starting with d_S = 4 cm for the proposed design, F_e is varied from -116 cm to -16.5 cm. For each F_e setting, the corresponding $2w_{min}$ of the laser spot is measured using the CCD at each resulting distance L. This w_{min} for a certain ECVFL focal length setting marks the minimum spot size of an optical writing head possible for a certain material substrate distance d_M which is also equal to L. Note that for a particular d_M, the spot size can be altered and increased via F_e variation, in which case d_M will no longer be equal to L. Once the $2w_{min}$ data for d_S = 4 cm is captured for the F_e range, the steps are repeated for d_S values of 8 cm and 12 cm. The measured data are presented in Fig. 4 plots as w_{min} vs. L for L values ranging from 20 cm to 800 cm.

Fig. 4 plots also includes a theoretical curve of expected w_{min} values computed using Eqn. (3) as well as a curve for the unconditioned Gaussian beam radii w_c given by Eqn. (5). Fig. 4 plots clearly show the difference in lowest achievable spot sizes between the proposed technique and the conventional unconditioned laser beam system. Throughout the 8 meter range, spot radii w_{min} are kept below 1 mm. As is seen in Fig. 4, larger d_S values correspond to smaller focussed spot radii, as explained by Eqns. (1), (2) and (3) put together. R^2 curves for the three d_S values are plotted and shown in Fig. 5. These curves quantify the factor increase in area using the proposed optical head design. The improvement is drastic even as the curves flatten out at the different d_S values, with the R^2 value approaching 150 for d_S = 12 cm, 75 for d_S = 8 cm, and 40 for d_S = 4 cm.

The Fig. 4 data shows the minimum size achievable using the prosed system with the given parameters. As mentioned earlier, for each substrate distance d_M, the size of the optical head is readily varied via ECVFL control. This allows not only precision cutting/ hole-punching into materials at different axial distances, it removes the need for expensive mechanical movable platforms as is required for unconditioned laser beam systems. Furthermore, the proposed design allows optical power density control via changing the power per unit area falling on substrate material. This power density control, which is coupled to changing optical head sizes, has potential applications for optically sensitive material requiring special incident power specifications.

4. CONCLUSION

Proposed and demonstrated in this paper is a smart optical writing head design which uses programmable optics to give the optical writing laser beam its size flexibility along with its optical power density control to match the material characteristics and the desired manufactured component physical size requirements. Writing head smartness stems from using an ECVFL coupled to a bias lens which gives optical writing head size control at different target distances. Suited to both continuous as well as pulsed wave sources, the proposed head design can be used in industries deploying laser-based cutting, machining and drill processes. A proof of concept experiment over a large range of 20 cm to 8 meters demonstrates the working principles of the proposed smart laser writing head design compared to raw unconditioned Gaussian laser beam based writing systems. Manufacturing applications for the smart optical writing head can include large sized components such as aircraft and automobile parts as well as smaller or micro-scale components including electronic, optical, micromechanical, and biomechanical components.

5. REFERENCES

[1] Chryssolouris, G., [Laser Machining: Theory and Practice] Mechanical Engineering Series, Springer-Verlag Berlin and Heidelberg GmbH & Co. K, (1991).

[2] Dubey, A.K. and Yadava, V., "Laser beam machining—A review," International Journal of Machine Tools & Manufacture 48(6), 609–628 (2008).

[3] Samant, A. N. and Dahotre, N. B. ,"Laser machining of structural ceramics—A review," Journal of the European Ceramic Society 29(6), 969–993 (2009).

[4] Modest, M. F., "Three-dimensional, transient model for laser machining of ablating/decomposing materials," International Journal of Heat Mass Transfer 39(2), 221-234 (1996).

[5] Ganesh, R. K., and Faghri, A., "A generalized thermal modeling for laser drilling process- I. Mathematical modeling and numerical methodology," International Journal of Heat Mass Transfer 40(14), 3351-3360 (1997).

[6] Meijera, J., Dub, K., Gillnerc, A., Hoffmannc, D., Kovalenkod, V.S., Masuzawae, T., Ostendorfc, A., Poprawec, R. and Schulzc, W., "Laser Machining by short and ultrashort pulses, state of the art and new opportunities in the age of the photons," CIRP Annals - Manufacturing Technology 51(2), 531–550 (2002).

[7] Kuar, A.S., Doloi, B. and Bhattacharyya, B., "Modelling and analysis of pulsed Nd:YAG laser machining characteristics during micro-drilling of zirconia (ZrO_2)," International Journal of Machine Tools and Manufacture 46(12–13), 1301–1310 (2006).

[8] Ghany, K. A. and Newishy, M., "Cutting of 1.2mm thick austenitic stainless steel sheet using pulsed and CW Nd:YAG laser," Journal of Materials Processing Technology 168(3), 438–447 (2005).

[9] Nikumb, S., Chen, Q., Li, C., Reshef, H., Zheng, H.Y., Qiu, H. and Low, D., "Precision glass machining, drilling and profile cutting by short pulse lasers," Thin Solid Films 477(1–2), 216–221 (2005).

[10] Amin, M. J., and Riza, N. A., "Smart laser scanning sampling head design for image acquisition applications," Applied Optics 52(20), 4991-4996 (2013).

[11] Hecht, E., [Optics], 4th Edition, Addison-Wesley 2001.

[12] Kogelnik, H. and Li, T., "Laser beams and resonators," Optical Society of America Applied Optics 5(10), 1550–1567 (1966).

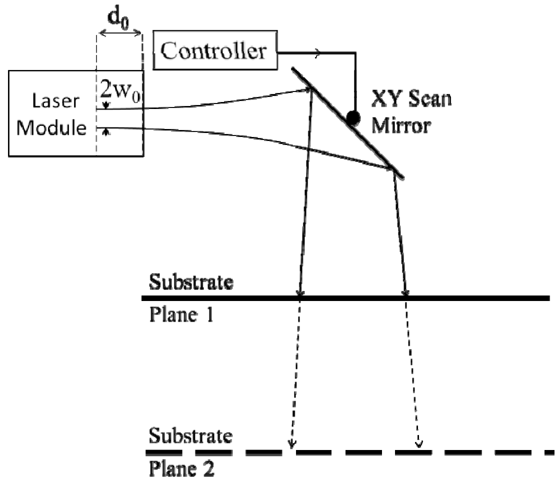


Figure 1. Non-smart (classic) point beam writing head using unconditioned laser beam propagation.

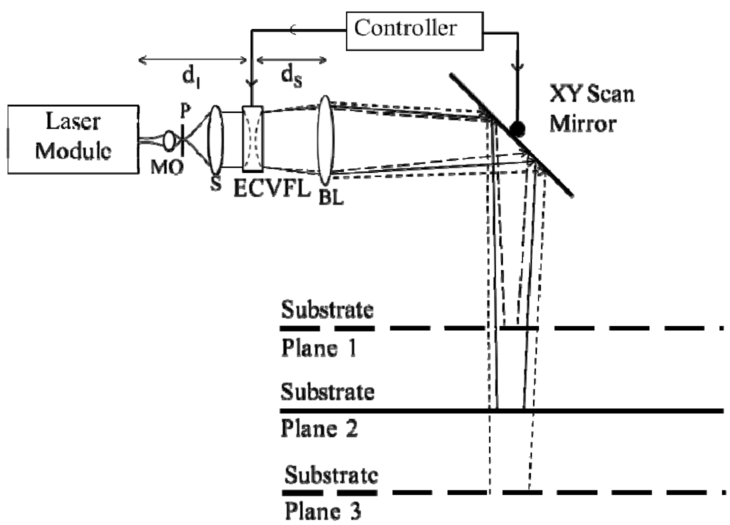


Figure 2. Proposed Smart Optical Writing Head Design.

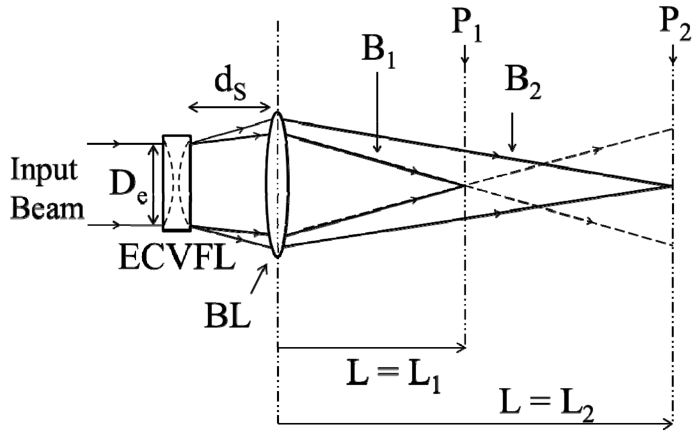
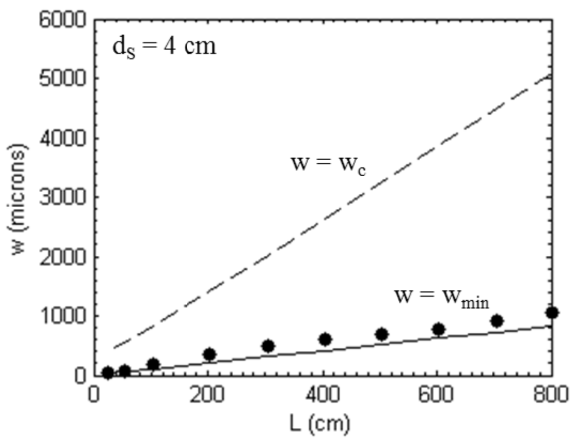
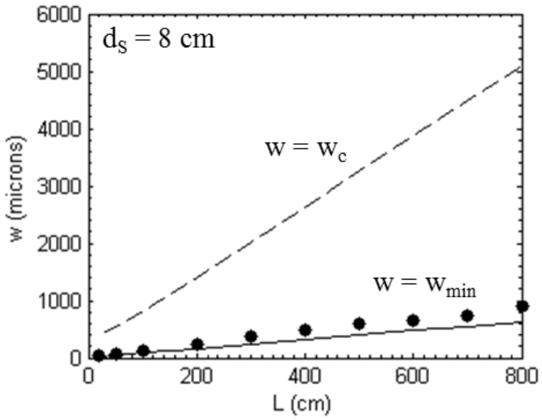


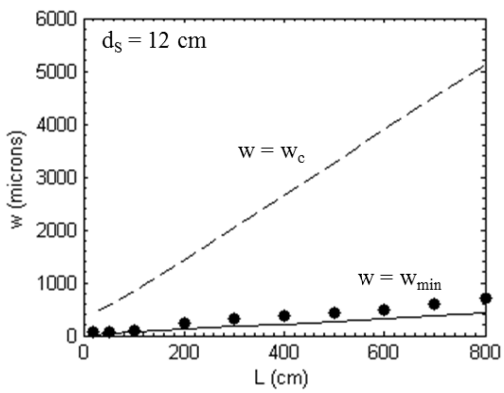
Figure 3. Combined ECVFL and BL focusing of two beams having different F_e settings giving different beam spot sizes.



(a)



(b)



(c)

Figure 4. Comparison of theoretical spot size for classic laser beam propagation (dashed lines) and Smart optical writing head design (solid lines) versus target distance. Figure shows theory and experimental data (dots) plots for the proposed design with d_S values of (a) d_S=4 cm, (b) d_S = 8 cm, and (c) d_S = 12 cm.

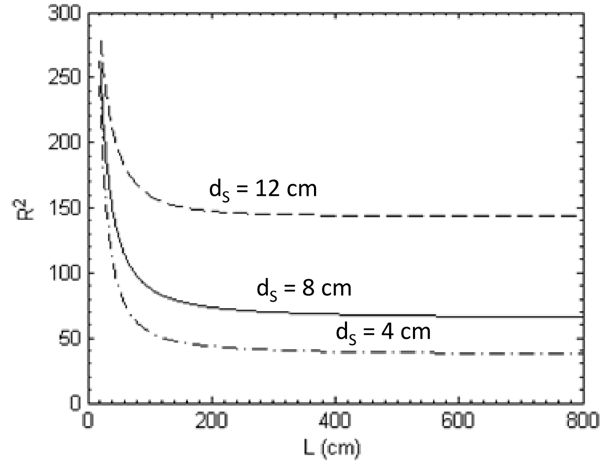


Figure 5. R^2 plots for the proposed smart optical head at d_S values of 4 cm, 8 cm and 12 cm.